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Assessing non-marginal variations with consequential LCA: Application to European energy sector

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ABSTRACT

Many policies are being designed to mitigate impacts of human activities on the environment. An environmental evaluation of these policies should include assessments of their impacts according to all known environmental impacts. Moreover, because policies may indirectly affect regions or economic sectors not initially targeted by these policies, indirect environmental consequences should be included in environmental balances. Life cycle analysis (LCA) is a holistic method made to assess environmental impacts caused by products or services according to various environmental damage categories. However, the ability of LCA to model environmental consequences due to a change is restricted to marginal changes occurring in small life cycles. New methodological developments are needed to study major changes and their environmental consequences as they may happen when a policy is applied at large scale. For that purpose, the economic general equilibrium model GTAP has been used to predict global economic perturbation that would be caused by two different European energy policies (bioenergy policy and business as usual policy). LCA was then used to assess environmental impacts due to European energy generation and perturbation of world economy. Despite the bioenergy policy involves more energy from renewable technologies which are expected to be less polluting, results show that due to rebound effects, bioenergy policy results in more environmental impacts. Combining both GTAP and LCA improves environmental assessment made with GTAP because it allows computing environmental impacts according to products life cycles instead of using economic sector emission factors and because emissions and extractions from environment are related to impacts on environment. Regarding LCA method, this new approach allows studying significant changes affecting large systems with a global modeling of economy in a time dependent environment. However, more work is needed to evaluate this new approach, especially uncertainty should be studied.

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1. Introduction

Many countries are currently aiming to reduce their consumption of fossil fuels[1] in order to decrease their energetic dependence and mitigate global warming. According to a large number of studies [1–11], substitution of fossil fuels by renewable energy production appears favorable regarding energetic dependence and global warming. For these reasons, the European Union[2] (EU) chose to expand its renewable energy generation system [12]. However, whereas the direct consequences of replacing fossil fuels with renewable energy sources are usually quite well documented at local scale (reduction of fossil fuels consumption that leads to a decrease in greenhouse gases (GHG) emissions), it is more difficult to assess the indirect consequences of that substitution at a global scale (e.g., indirect land use changes caused by increase in biofuel production). Moreover, it has been demonstrated that, in some cases, the GHG emissions caused by the indirect consequences of biofuel production can be higher than the decrease of the emissions attributed to oil substitution [13,14]. This indicates the need to evaluate renewable energy policies at a larger scale to include indirect consequences.

Among available holistic environmental assessment methods, life cycle assessment (LCA) as defined in ISO standards (ISO 14040:2006 and ISO 14044:2006), is probably the most comprehensive. The objective of LCA is to compile all flows of matter and energy related to the life cycle of a studied system and to evaluate the related potential environmental impacts. It does not only focus on a specific environmental aspect such as climate changes, but draws a global portrait of potential environmental impacts caused by a life cycle and thus, is able to model environmental impact displacements between life cycle stages or impact categories. LCA was developed to assess the environmental impacts that can be attributed to a specific product system (attributional LCA or A-LCA) and not to describe the potential consequences on other product systems of changes in the studied system. At the end of the nineties, some developments in LCA methodology [15–18] allowed adaptation of the method into a tool that supports the environmental evaluation of such changes (consequential LCA or C-LCA). However, C-LCA is still under development and no consensus has been reached on the method [19]. The main idea of C-LCA is to include in the assessment the consequences of a change affecting the initial product system studied, and which may affect other life cycles not connected by mass or energy flows to the studied system.

An example of a C-LCA context would be to consider increasing wood production in a particular region that could be achieved by using more land in that region. However, this land may already be used for farming corn. In that case, at local scale, increasing wood production would cause a decrease in corn production. However, at global scale, corn production must address overall corn demand and therefore some corn (or a corn substitute) would need to be produced in another region. For this type of situation, basic economic models and time series are often used to identify and model economic links between life cycles [20–27]. Moreover, up until now, most C-LCAs have been conducted on small systems affected by marginal variations [23,24,28–32] or by restricting studied consequences [33–35] and it is unclear how C-LCA should be undertaken on large systems affected by non-marginal variations. Bureau et al. [36] note also that due to non-linear environmental impacts related to the biofuel life cycle, the LCA method is currently not adapted to study non-marginal variations of biofuel production.

Therefore, to assess a large perturbation affecting a large system such as a significant European substitution of fossil fuels by renewable energies, a new C-LCA method is required. While the principle of the C-LCA remains the same for studying both small and large systems, the methodology needs to be adapted for large systems because non-marginal perturbations involve significant volumes of goods that may affect in a non-linear way the price, the production and the consumption of commodities for a long period leading to non-linear environmental impacts. For that reason, basing the identification of indirect consequences caused by large changes only on basic economic models and past tendencies that are widely used to study marginal changes may be misleading since they are not able to model non-linear effects.

According to Berck and Hoffmann [37], non-marginal variations should be studied with a computable general equilibrium model (CGEM) in order to take into account price variations and non-linear effects on each economic sector including those which are indirectly affected by the perturbation. More specifically, Kretschmer and Peterson [38] agree that bioenergy policies cannot be studied without taking into account all economic sectors because of direct and indirect relationships between bioenergy and the economy.

The objective of this paper is to illustrate a new approach based on the use of sequential application of CGEM and C-LCA to assess the environmental impacts of different energy policies. More specifically, the substitution of fossil fuels by renewable energies in Europe is addressed with a focus on EU electricity and heat generation between 2005 and 2010.

2. Method

Environmental impacts were assessed according to the LCA methodology described in relevant ISO standards (ISO 14040:2006 and ISO 14044:2006). However, rather than conduct a regular attributional LCA, a consequential approach was followed in order to include indirect impacts caused by two different European energy policies. A distinction has been made between direct and indirect environmental impacts. Direct impacts are caused by increase of electricity and heat generation during the studied period. It was assumed that extraction of raw materials and plant construction are also accounted for direct impacts. Indirect impacts stem from perturbations of the world goods production caused by the variations in extraction of raw materials used to produce EU electricity. The proposed method, summarized in Fig. 1, is based on the application of several tools:

1. changes in European electricity system and evolution of world economy are used to run economic model GTAP which simulates changes in production of all economic sectors;
2. GTAP database is mapped to public databases in order to compute the mass of commodities produced by each economic sector and energy generated in 2005;
3. GTAP database is mapped to ecoinvent LCA database as to establish the emissions and extractions from ecosystems caused by each economic sector;

[1] Coal, natural gas and oil.
[2] 25 members.

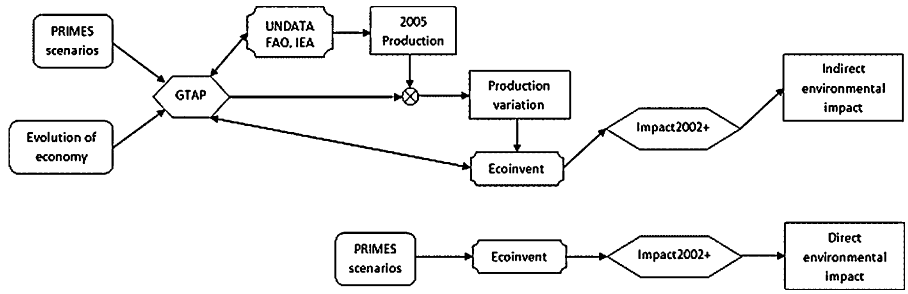

Fig. 1. Method overview.

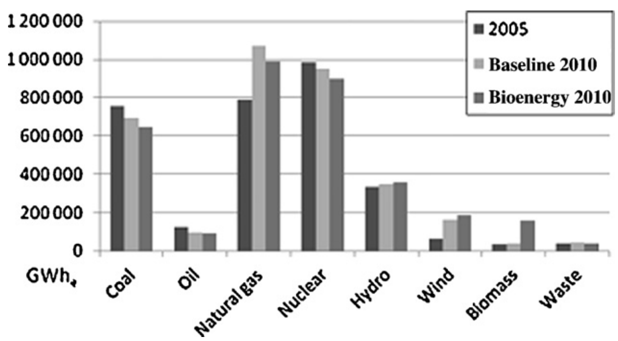

Fig. 2. Generation of electricity by source of power between 2005 and 2010 (adapted from Mantzos et al. [19])

4. Impact2002 + method is applied to compute potential indirect environmental impacts;
5. Direct environmental impacts are assesses directly from European electricity generation according to LCA method with ecoinvent database and Impact2002 + method.

The next paragraphs details each step of the method.

2.1. Description of the energy policy studied

Two scenarios have been used to model the implementation of two different EU energy policies. These scenarios are adapted from Mantzos et al. [39] and were initially undertaken to predict variations among sources of energy according to various EU energy policies up to 2030. Mantzos et al. [39] used the PRIMES model, a partial equilibrium model for the European energy system, to generate these scenarios[3].

The first scenario, called *Baseline scenario*, is a business as usual scenario where 2000s EU energy policy is maintained in the future. The second scenario, called *Bioenergy scenario*, involves a higher rise of renewable technologies, especially electricity from biomass (cf. Fig. 2). This scenario was chosen because it presents a significant variation in the amount of wood used to produce electricity. Thus, it was expected that the wood demand variation would result in a perturbation of construction, manufacture of furniture, and paper markets because all of these markets involve wood products. In this paper, modeling innovation of technologies and emergence of new technologies was avoided by restricting the studied period to 2005–2010 instead of 2005–2030 as it is in the Mantzos et al. [39] scenarios, assuming that technologies remain the same during the 2005–2010 period. However, the intent is to extend the current work to include the post-2010 period in future work. These scenarios were written before 2005, therefore the 2005–2010 period is described by 2 scenarios instead of using real data (such data were not known when scenarios where written). This should not be seen as a problem because the main goal of this study was to develop a new method to assess environmental impacts caused by policy rather than to compute accurate environmental impacts of EU energy policies.

2.2. Indirect environmental impacts

Indirect environmental impacts are a result of a ripple effect caused by European energy scenario on the world economy. Thus, a modeling of global markets for each economic sector was undertaken and results of economic model were subsequently used to compute estimated potential environmental impacts.

2.2.1. Indirect economic consequences of energy policies

The GTAP computable general equilibrium model [40] was chosen because of its very detailed database (GTAP7), its open source code, and the large community of users using it. GTAP was used to describe the increases and decreases in production of 57 economic sectors in 113 world regions in response of European energy policies and economic growth.

Running the GTAP model with its completely disaggregated database was not practical due to a lack of computer resources. Thus, the GTAP database was aggregated into 20 commodities and 13 regions allowing individual modeling of electricity sources (except uranium extraction, which cannot be easily disaggregated from the mining sector) and wood-related activities (c.f. Table 1 and Table 2).

Because most of the changes of EU energy system described in Mantzos et al. [39] affect the electricity sector and because transport modeling in GTAP database is too aggregated, changes in fuels for transport sector describes in Mantzos et al. [39] were not included in this study.

To model changes in mass of fuels used to produce energy, GTAP source code was slightly modified to express demand variations in terms of mass instead of monetary value. For that purpose new mass variables were created from percent value variations of demand minus percent price variations for each commodity in each region.

Macroeconomic variables (population, gross domestic product (GDP), capital, skilled and unskilled labor) changed between 2005 and 2010; therefore, their variations were included in simulations to reflect economic growth. Data were obtained from various sources: population and gross domestic product from the US government [41], capital from a previous study undertaken using GTAP [42], and unskilled and skilled labor from an international association [43].

GTAP simulations were then conducted by shocking exogenous demand variables according to the future needs of forestry and wood products, coal, natural gas and oil used to produce electricity and heat as described in [39].

[3] Some results of POLES (another partial economic model for energy system) have also been used by Mantzos et al. [39].

Table 1
Definition of GTAP regions.

GTAP region (description)	Member countries
Oceania	Australia, New-Zealand, American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall, Micronesia, Nauru, New Caledonia, Norfolk Island, Northern Mariana Islands, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis and Futuna
China	China
EastAsia	Hong-Kong, Japan, Korea (north and south), Taiwan, Macau, Mongolia
SEAsia (South East Asia)	Cambodia, Indonesia, Lao, Myanmar, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Brunei Darussalam, Timor Leste
SAsia (South Asia)	India, Pakistan, Bangladesh, Sri Lanka, Afghanistan, Bhutan, Maldives, Nepal
NorthAmer (North America)	Greenland, Canada, United States, Mexico, Bermuda, Saint Pierre and Miquelon
LatinAmer (Latin America)	Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Falkland Islands, French Guiana, Guyana, Suriname, Belize, Costa Rica, Guatemala, Nicaragua, Panama, El Salvador, Honduras, Antigua and Barbuda, Bahamas, Barbados, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and Grenadines, Trinidad and Tobago, Virgin Islands (US and British), Anguilla, Aruba, Cayman Islands, Cuba, Guadeloupe, Martinique, Montserrat, Netherlands Antilles, Turks and Caicos
Brazil	Brazil
EU_25 (European Union)	Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom
RestofEU (Rest of Europe)	Norway, Switzerland, Albania, Bulgaria, Croatia, Romania, Iceland, Liechtenstein, Andorra, Bosnia and Herzegovina, Faroe Island, Gibraltar, Macedonia, Monaco, San Marino, Serbia and Montenegro, Moldova
MENA (Middle East and North Africa)	Egypt, Morocco, Tunisia, Algeria, Libya, Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Palestinian occupied territory, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen, Iran, Turkey
SSA (Sub-Saharan Africa)	Nigeria, Senegal, Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe, Botswana, South Africa, Benin, Burkina Faso, Cote d'Ivoire, Cape Verde, Ghana, Guinea, Guinea-Bissau, Gambia, Liberia, Mali, Mauritania, Niger, Saint Helena, Sierra Leone, Togo, Central African Republic, Cameroon, Congo, Gabon, Equatorial Guinea, Sao Tome and Principe, Chad, Angola, Congo, Burundi, Comoros, Djibouti, Eritrea, Kenya, Mayotte, Reunion, Rwanda, Somalia, Sudan, Seychelles, Lesotho, Namibia, Swaziland
RestofWorld (ex-USSR)	Russian Federation, Ukraine, Kazakhstan, Kyrgyzstan, Armenia, Azerbaijan, Georgia, Tajikistan, Turkmenistan, Uzbekistan, Belarus

2.2.2. Computing variations of masses and energy from GTAP results

Because variations in masses are required by ecoinvent to compute environmental impacts, a second modification was made to the GTAP source code to express production variations in terms of mass instead of monetary value. For that purpose new mass variables were created from percent value variations minus percent price variations for each commodity in each region. Additionally, it was necessary to define the mass of each commodity produced in each region for the year 2005. Various sources of data were used for that purpose: FAOSTAT (crop and livestock sectors), ForesSTAT (forestry, wood and paper sectors), AQUASTAT (water purification sector) and UNDATA (all other sectors). In the case of electricity sector, electricity quantities produced in 2005 where obtained from International Energy Agency database. GTAP percent variations of production were subsequently applied to calculate variations of masses and electricity generation occurring during 2005–2010 for the production of each commodity in each region.

2.2.3. Mapping GTAP7 to LCA database

Estimated potential environmental impacts can be calculated from the expenses of each economic sector (using an Input/Output (I/O) database) or from the mass of products produced (using a process database). I/O databases express environmental impacts according to expenses made in economic sectors while process databases compute emissions and extractions of substances according to process life cycles and then environmental impact can be evaluated by using impact assessment methods.

Table 2
Definition of GTAP economic sectors.

GTAP sector	Description	Detail
GrainsCrops	Grains and crops	Paddy rice, wheat, cereal grains, vegetables, fruit, nuts, oil seeds, sugar cane, sugar beet, plant-based fibers, crops, processed rice
MeatLstk	Livestock and meat products	Cattle, sheep, goats, horses, other animal products, raw milk, wool, silk-worm cocoons, fishing
ProcFood	Processed food	Vegetable oils and fats, dairy products, sugar, food products, beverages and tobacco products
Water	Water	Collection, purification and distribution of water
TextWapp	Textiles and clothing	Textiles, wearing apparel
LightMnfc	Light manufacturing	Leather products, metal products, motor vehicles and parts, transport equipment, manufactures.
HeavyMnfc	Heavy manufacturing	Chemical, rubber, plastic prods, mineral products, ferrous metals, metals, electronic equipment, machinery and equipment
Util_Cons	Utilities and construction	Construction
TransComm	Transport and communication	Land transport, transport via pipelines, water transport, air transport, post and telecommunications
OthServices	Other services	Financial services, insurance, business services, recreation and other services, public administration, defense, health, education, dwellings.
coa	Coal and lignite extraction	Mining and agglomeration of hard coal and lignite
gas	Gas extraction	Extraction of natural gas, service activities incidental to natural gas extraction excluding surveying
oil	Oil and peat extraction	Extraction of crude petroleum, service activities incidental to oil extraction excluding surveying
omn	Minerals	Mining and quarrying (including uranium)
p_c	Fuels	Manufacture of coke oven products and refined petroleum products, processing of nuclear fuel
gdt	Gas, steam and hot water	Manufacture of gas, distribution of gaseous fuels through mains, steam and hot water supply
ely	Electricity	Production, collection and distribution of electricity
frs	Forestry	Forestry, logging and related service activities
ppp	Pulp, paper, publishing	Manufacture of paper and paper products, publishing, printing and service activities related to printing
lum	Wood products	Manufacture of wood and of products of wood and cork, except furniture, Manufacture of articles of straw and plaiting materials

Table 3
Modeling of GTAP economic sectors in ecoinvent.

Partially modeled	Not modeled
Food transformation (ofd) and textiles (txt)	Wearing apparel (wap), motor vehicles (mvh), transport equipment (otn), manufactured products (omf), electronic equipment (ele), machinery and equipment (ome), construction (Util_Cons), transport related sectors (otp, wtp, atp) and tertiary sectors (trd, cmn, ofi, isr, obs, ros, osg and dwe)

A challenge when using an I/O database is that there is no consensus on how to build such databases. Thus, different countries may have inconsistent I/O databases and none of them have been designed at a global scale. I/O databases are not available for all countries, but proxies can be made by using the same I/O database for several countries. However, doing this increases uncertainty because:

1. The economy differs between countries. Thus, expenses within a specific economic sector may not lead to the same production of the same goods in two different countries; and
2. Technology differs between countries, and therefore environmental impacts to produce a product may differ among countries.

Process databases also suffer limitations: they are made to model processes occurring in a specific geographical context and because there is no consensus on how to build that kind of database, using different process databases leads to inconsistent results [44]. To avoid that problem, a single process database can be used to model all regions. Among LCA databases, ecoinvent is often chosen because it has many more processes than all other currently available databases and the quality of data is reputedly high. However, using a single process database for all world regions contributes to an increased uncertainty because technologies differ between regions. To avoid uncertainty related to the economy from the use of I/O databases and problems in consistency of data between regions, ecoinvent was chosen to model processes in this study.

To convert variations of masses into environmental impacts, a mapping of GTAP7 with ecoinvent was undertaken. Because ecoinvent has only a few processes to model the food sector, some additional processes were created based on the Danish LCA food database. However, due to an overall lack of process details, some economic sectors[4] were partially or not modeled:

In the case of the "transport and communication" sector, a lack of regional transport and communication data prevented mapping this sector with ecoinvent. Nevertheless, transport processes are included in ecoinvent for each process as background processes, and thus transport environmental impacts are modeled through each economic sector instead of as one overall transport sector. Tertiary sectors (trd, cmn, ofi, isr, obs, ros, osg and dwe) were not modeled as it would have been too time-consuming, given that many LCAs would have been required for modeling each of these sectors.

2.2.4. Ecoinvent modifications

Electricity is involved in all life cycles and can have significant environmental impacts. Thus, electricity generation systems for each region have been modeled specifically to take into account regional diversity. In that regard, regional ecoinvent processes for electricity generation were used where available and proxies were developed for countries not covered by ecoinvent data (e.g.: Japanese processes were used for South Korea). For countries not included in ecoinvent, the proportion of each electricity generation technology was modeled according to 2005 data from the International Energy Agency database [45].

More than one economic sector is often involved in one ecoinvent process. Therefore, it was necessary to segment the ecoinvent database according to the GTAP economic sectors in order to avoid double counting of indirect environmental impacts. For this reason, all inputs and outputs for each process involved in GTAP7-ecoinvent correspondence were removed. Thus, if a process used in the database involves a process that is also used in the database in its life cycle, then environmental impacts are not counted twice.

2.2.5. Evaluating indirect environmental impacts

Environmental impacts were calculated with a widely used method in LCA: Impact2002 + [46]. This method converts the emission of pollutants and the extraction of natural resources[5] into 14 environmental impacts categories according to cause and effects chains for each material. By using a unique unit for each category, these impacts can then be aggregated into four damage categories (human health, ecosystem quality, climate change and resource consumption). Indirect environmental impacts of EU energy scenarios were assessed according to the inventory of matters and energy modeled with ecoinvent processes from variations in the electricity generation[6] and the mass of each commodity produced in each region between 2005 and 2010. As it is a common procedure in LCA studies, environmental impacts were also computed with another impact assessment method as to evaluate the results obtained. In this study, Recipe was chosen as an alternative impact assessment method. Recipe, described in [47], differs from Impacts2002 + in hypothesis, effects chains and impacts categories.

2.3. Direct environmental impacts

Direct environmental impacts were modeled according to the variation of the amount of electricity produced by each technology between 2005 and 2010 for a given scenario. A correspondence between technologies described in Mantzos et al. [39] and processes available in ecoinvent 2.0 was conducted. By doing this, some technologies such as hydrogen power were excluded from the study due to their small contribution to European electricity production.

3. Results

In this section, potential environmental impacts of both policies are assessed and discussed. A comparison of these impacts is subsequently made to assess which scenario would be less damaging from an environmental perspective.

3.1. Effect of the Economy Evolution versus of the EU policies

Environmental impact assessment shows that most estimated impacts are caused by the anticipated evolution of the economy between 2005 and 2010 rather than the two EU scenarios studied. For the period studied, the average estimated impacts on global warming for each EU scenario are two magnitudes of order lower than those from the anticipated evolution of the economy (Fig. 3). This result can be explained by GTAP's highest sensitivity to macroeconomic variables that reflect the evolution of the economy (particularly gross domestic product, which has a significant effect

[4] See Table 3 for more details.

[5] Including those used to produce energy.

[6] Excluding EU which is modeled in direct environmental impacts.

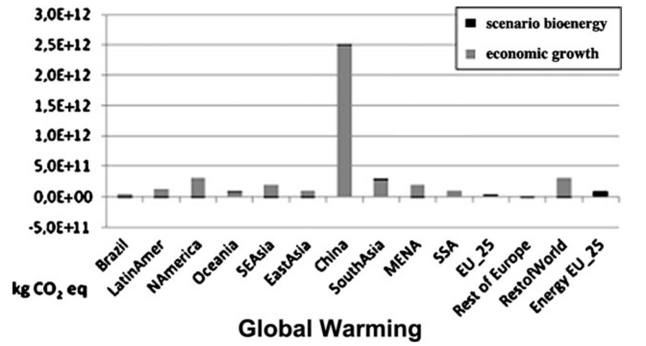

Fig. 3. Comparison of 2005–2010 GHG emissions caused by evolution of economy and EU scenario by region.

on the production of each economic sector), rather than to changes in demand for the commodities required to produce electricity.

Because GTAP models the economy by region, estimated environmental impacts can be expressed according to the place where they would occur (assuming the entire life cycle of selected processes does not cross into multiple regions). In both scenarios, China, South Asia and ex-USSR (RestofWorld) are globally the most affected regions, followed by North America, Middle East and North Africa (MENA) which also show some significant potential impacts for global warming and resources (cf. Fig. 4). The rest of Europe (non-EU countries) has the lowest potential impacts in most of the categories.

These results can be interpreted largely through macroeconomic variables.

- Important potential impacts in China and South Asia are related to high increases in GDP (+60% and + 43%) between 2005 and 2010 due to emerging markets.
- Low potential impacts in the rest of Europe are related to a low increase in GDP (+11%) due to existing mature economies and low economic growth on that period.
- Moderate potential impacts in the ex-USSR are a result of moderate GDP increases (+22%) and a low increase in the skilled labor force (+5% in comparison to other regions average + 17%). In North America, most of the green house gases emissions during the studied period are caused by electricity generation. Despite a slow increasing GDP (+6%) in North America, the amount of electricity produced in 2005 is already so significant that even a small percent increase in electricity production causes significant potential environmental damages. Natural Resources consumption in Middle East and North Africa are related to oil extraction which increases by 10% according to GTAP model.

Beyond presentation of results at a regional level, GTAP results can also be expressed by economic sector (cf. Fig. 5). At a global scale, it appears that the electricity, grain and crop, livestock and meat products, mining, oil and coal extraction, and water purification sectors represent an average of 90% of the estimated proposed environmental impacts for all IMPACTS 2002 + damage categories. Interestingly, most of the processes responsible for these potential effects can be identified for each damage category:

- Human health: electricity generation (especially in China, South Asia and North America), Chinese extraction of coal, beef, pig and sheep livestock, primary aluminum copper, iron and nickel production (especially South East Asia for nickel), sugar cane wheat and rice plantations, folding boxboard and kraft paper production, drinking water treatment and crude oil extraction;
- Ecosystems: beef, pig and sheep livestock, rice, wheat, corn potatoes, rape seed, barley, cotton, grape, sugar cane and sunflower plantations, rape seed oil and wine production, logs, plywood, folding boxboard and kraft paper production, zinc, copper, aluminum and nickel primary production and crude oil extraction;
- Global warming: electricity generation (especially in China and North America), Chinese extraction of coal, aluminum primary production, beef and pig livestock, rice, corn and wheat plantations, corrugated board production; and
- Resources consumption: coal, oil and uranium extraction.

It should be noted that most of these processes are related to energy (which is linked to GDP variation since energy is used in most industrial and agricultural processes) and food production (linked to population growth).

These types of results may be helpful for policy makers to focus their effort on the activities with the greatest potential for environmental effect.

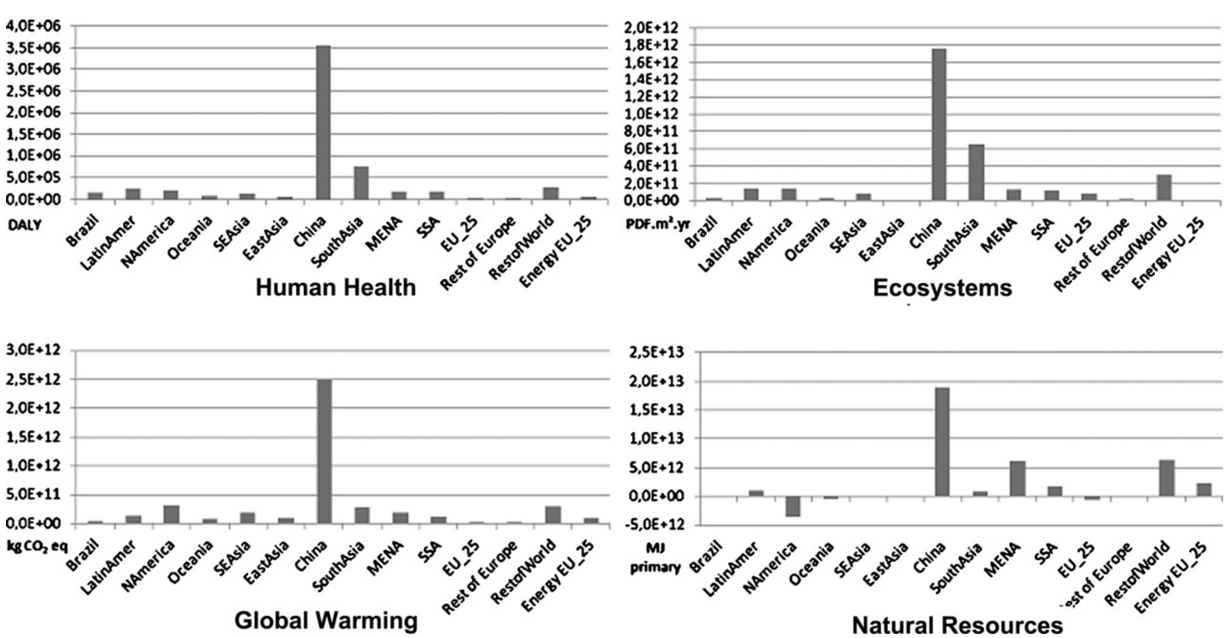

Fig. 4. Potential life cycle impacts of 2005–2010 EU bioenergy scenario by impact category and by region based on Impact 2002+.

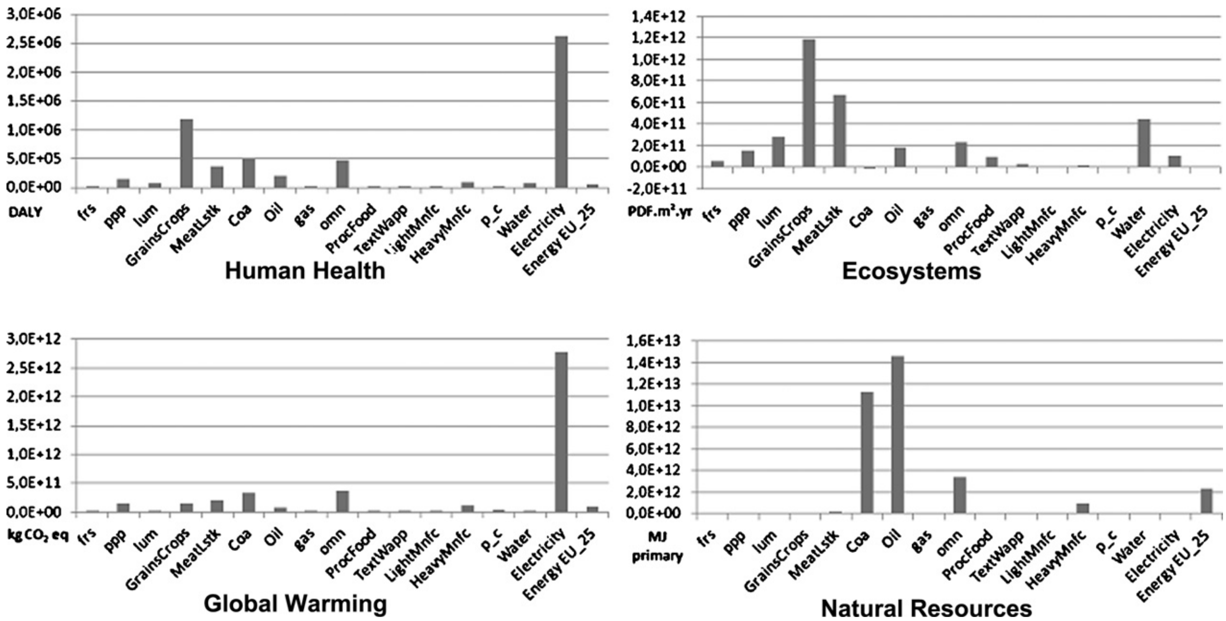

Fig. 5. Potential impacts of 2005–2010 EU bioenergy scenario by impact category and by economic sector based on Impact 2002+.

It was anticipated that the forestry, wood and paper sectors would be more affected in the bioenergy scenario than in the baseline scenario. GTAP results show that increases in production for these three sectors are globally higher in bioenergy scenario. At a regional scale, the EU and ex-USSR are the most affected regions. That said, the 2 most affected sectors are coal and natural gas extraction and then, at third place, the wood sector, despite the fact that variations in demand were higher for wood and forestry sectors.

The necessity for including the evolution of the economy in GTAP simulations despite economic evolution is the same for both EU energy policies is justified because GTAP is a non-linear model. Thus the calculation of a new economic equilibrium caused by a perturbation (EU scenario) will result in a different equilibrium if the evolution of economy is or is not taken into account. Simulations without incorporating economic evolution have been run and results differ substantially from results shown above. For instance, global environmental impacts in simulations without evolution of economy are underestimated by about two orders of magnitude and highly differ for all regions and economic sectors (cf. Figs. 6 and 7). It could also be shown that comparing potential environmental impacts for each EU energy scenario without taking account of economic evolution would lead to erroneous conclusions.

3.2. Comparison of the two scenarios

To evaluate which scenario is preferred from an environmental perspective, direct and indirect estimated potential environmental impacts of the baseline scenario have been subtracted from those of the bioenergy scenario for each damage category, each region and each economic sector (cf. Figs. 8 and 9). Several observations can be made by comparing both energy scenarios. First, at the Euro-

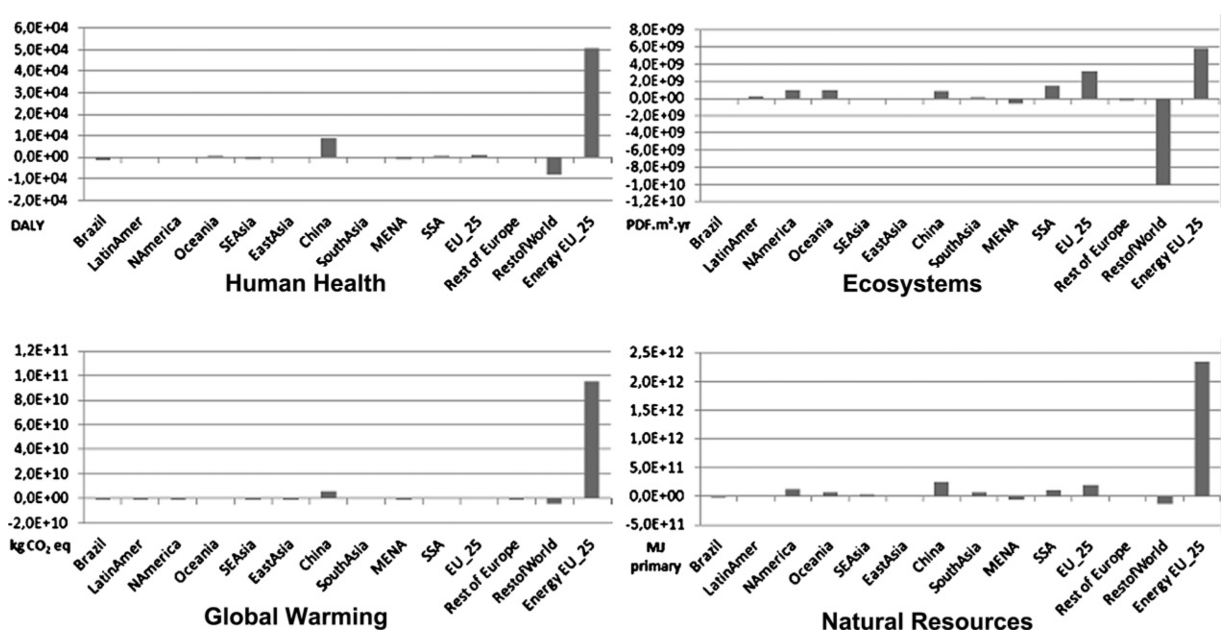

Fig. 6. Potential life cycle impacts of 2005–2010 EU bioenergy scenario by impact category and by region based on Impact 2002+ and without taking into account the evolution of economy.

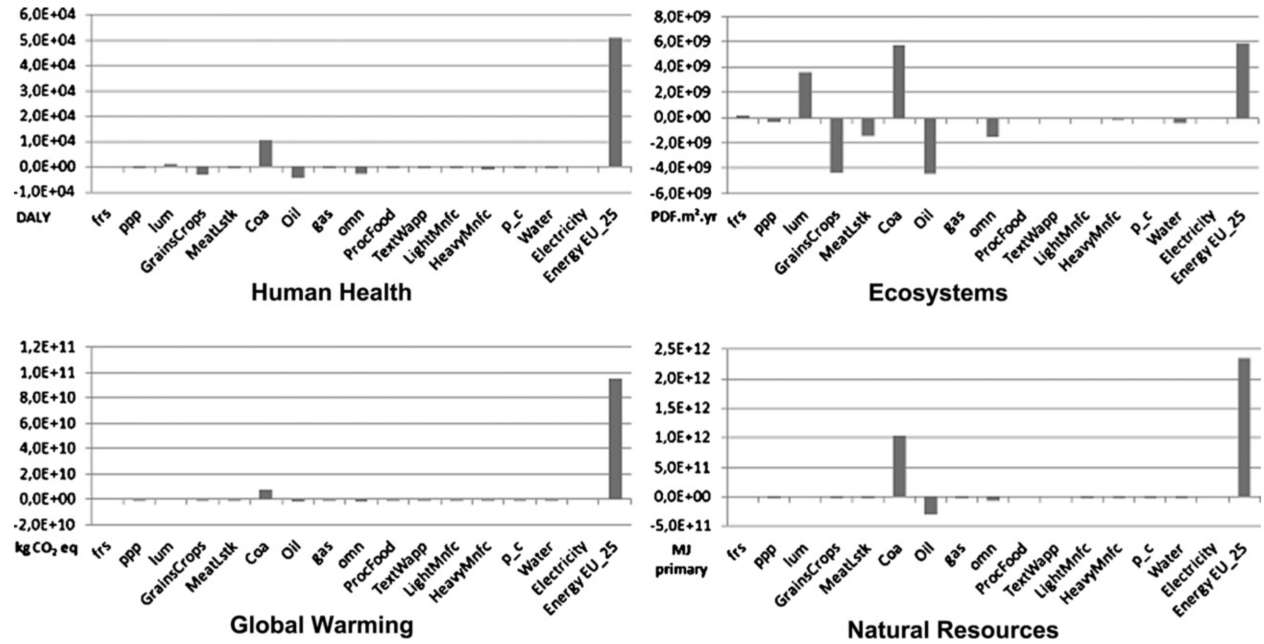

Fig. 7. Potential life cycle impacts of 2005–2010 EU bioenergy scenario by impact category and by economic sector based on Impact 2002+ and without taking into account the evolution of economy.

pean scale, indirect potential impacts of both scenarios are quite similar while direct potential impacts are higher for the baseline scenario in the case of the global warming and human health indicators. In the case of the ecosystems and resources consumption indicators, the bioenergy scenario causes more potential impacts than the baseline scenario. Thus, at the European scale, it cannot be determined which scenario causes the less impact to the environment without setting priorities among impact categories. Second, at the global scale, the potential indirect impacts of the bioenergy scenario are considerably higher than those of the baseline scenario. Moreover, global potential indirect impacts are higher than direct impacts. Consequently, at the global scale and for all damage categories, the bioenergy scenario causes more potential impacts to the environment than the baseline scenario. It can also be seen that for all regions and impact categories (except South Asia for ecosystems and the Middle East and North Africa for ecosystems and resources consumption), the bioenergy scenario causes more potential impacts than the baseline scenario.

These observations illustrates that it would be misleading to consider only the impacts occurring inside EU borders due to each scenario, because this would take into account only a small part of overall environmental impact (5.5% of total global potential impacts according to an average made on all impact categories).

Another observation that can be made is that most of the differences between the environmental impacts across the two scenarios occur in sectors related to coal extraction (including lignite) and

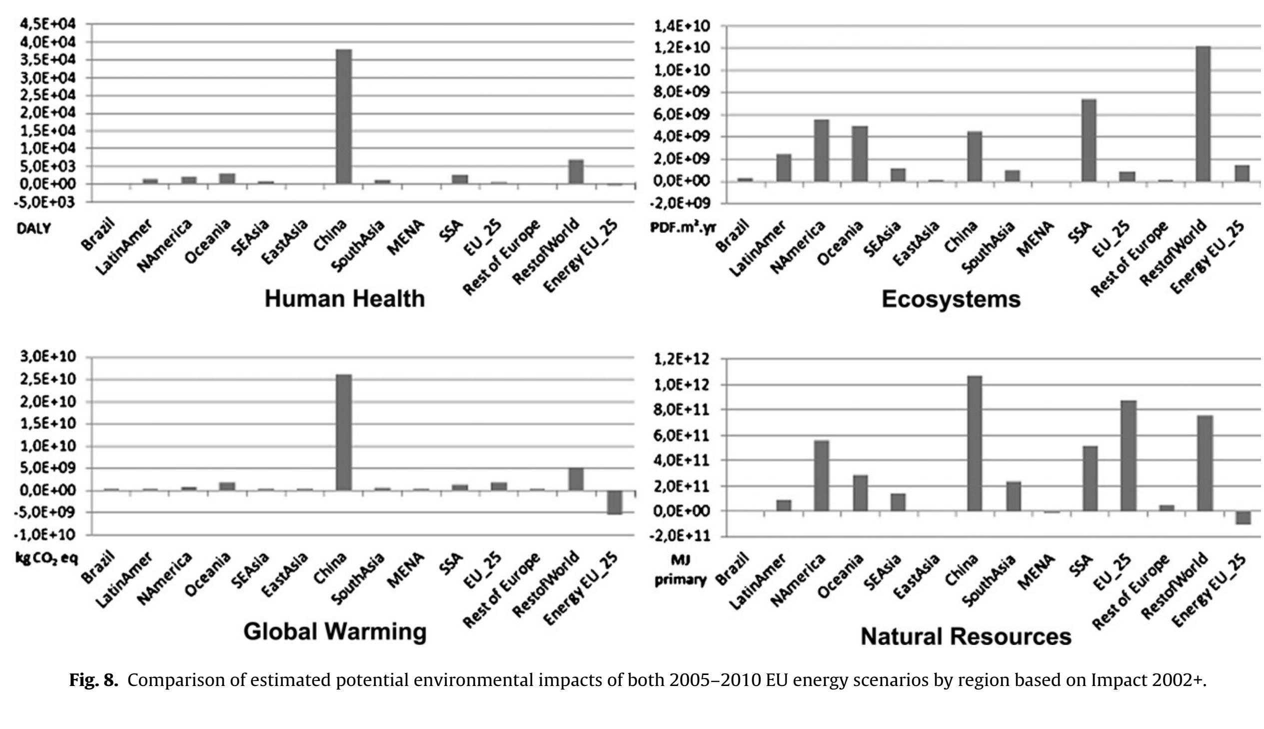

Fig. 8. Comparison of estimated potential environmental impacts of both 2005–2010 EU energy scenarios by region based on Impact 2002+.

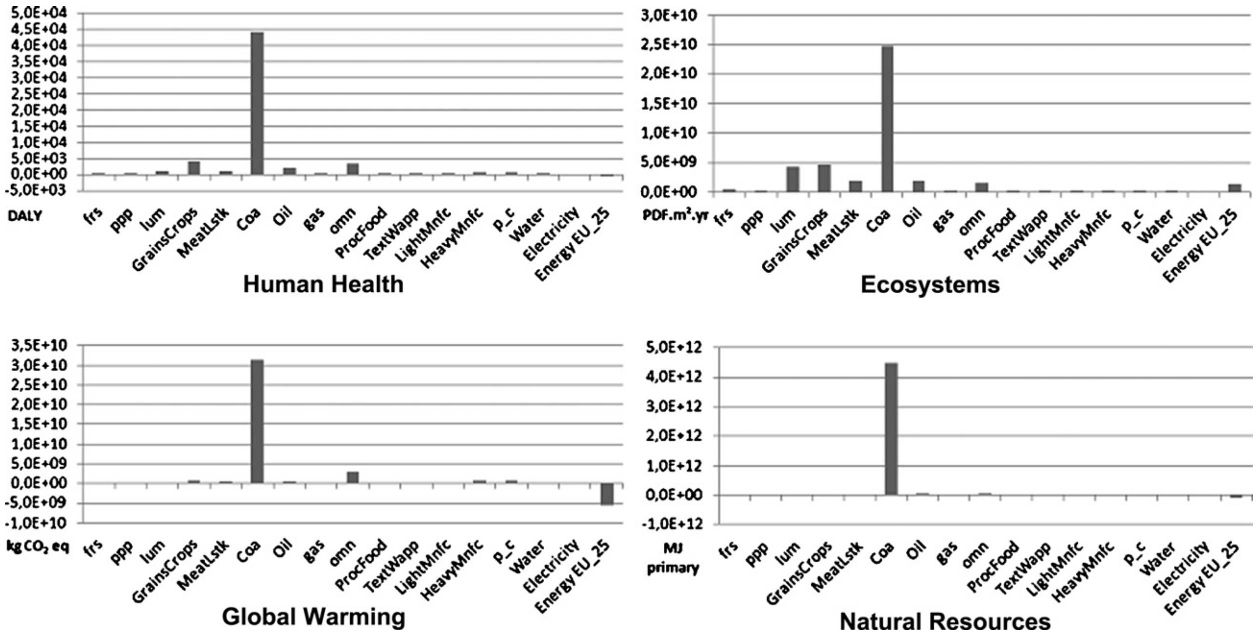

Fig. 9. Comparison of estimated potential 2005–2010 environmental impacts of both EU energy scenarios by economic sector based on Impact 2002+.

electricity generation (average of 95.5% of indirect impacts and total impact). This means that the results presented here could probably be improved by enhancing the modeling for a few economic sectors rather than for all economic sectors. As an improvement, partial equilibrium models for these sectors could be linked to GTAP in recursive simulations and more accurate data could be sought for improving modeling of involved processes.

Regarding, coal/lignite extraction, it is higher in the bioenergy scenario than in the baseline scenario. This unexpected result can be characterized as a rebound effect. In the bioenergy scenario, European consumption of coal and lignite is estimated to be reduced by 17% in the electricity sector. This leads to an estimated 23% reduction in imports of coal and lignite from regions outside the European Union and an increase of 24% in the export of coal and lignite from the European Union to other regions. Coal and lignite prices are also affected this way:

- World market prices of coal and lignite supplied from the European Union to all other regions decreases (mean variation −7%), while these prices are increasing in all other cases (mean variation +7%);
- Supply prices and export prices of coal and lignite in the European Union decrease (mean variation −7%), while these prices are increasing in all other regions (mean variation +8%); and
- Domestic prices of coal and lignite decrease in the European Union (−6%), while they are increasing in all other regions (+7%).

Due to the reduction of supply prices, coal and lignite production in the European Union increases (+7%). Thus, more coal and lignite are available for export and for local consumption. The reduction of domestic prices of coal and lignite would encourage all economic sectors (excepted electricity and heat, which are regulated by European energy scenario) to increase their demand in coal and lignite (mean variation +12%). Finally, primarily China, but also Oceania, North America, Sub-Saharan Africa and ex-USSR, are more strongly affected than other regions in the bioenergy scenario than in the baseline scenario. According to the GTAP7 database, the European Union is the primary trading partner of ex-USSR, Oceania and North America and the secondary trading partner of China. EU exports represent 45% of ex-USSR imports, 23% for Oceania, 17% for North America and 14% for China. Therefore, it is expected that a change in the EU economy would affect these regions.

More in-depth interpretation of this rebound effect is difficult because of the large number of parameters used by GTAP simulations. This could be seen as a weakness of using complex macroeconomic models like GTAP; however, it could also be reasonable to think that all results generated by a model that count hundreds of variables, parameters and equations cannot be easily predicted and should be accepted according to the model limits.

4. Discussion

Combining both GTAP and LCA have shown to improve environmental assessment over using GTAP or C-LCA separately.

1. The combined modeling approach provides an economic framework to model large systems affected by significant changes in consequential LCA studies. Thus, economic consequences of large perturbations can be determined by GTAP instead of being investigated with inadequate basic models or uncertain economic hypotheses [20–27,48,49]. Moreover, this approach allows answering the question "what economic sectors will be affected by the studied perturbation and which one(s) should be modeled?" given that all sectors are modeled by GTAP. Thus it allows including more economic sectors (but not all due to ecoinvent limitations) and their potential consequences on modeling results.
2. A combined modeling approach provides information about where the consequences of changes are anticipated. Thus, it becomes possible to use regionalized data for most regions of concern to model the most affected processes and assess environmental impacts (as has been done for electricity generation). This possibility is of great interest since industrial processes and environmental mechanisms that lead to potential environmental damage may differ between regions [50,51]. Moreover, by using environmental impacts expressed by economic sector (cf. Fig. 8), the LCA processes that cause most of the environmental impacts can be identified (c.f. Table 4 in Annexes). Consequently, efforts to collect better data on industrial processes can be optimized by reducing the number of processes

Table 4
Processes that contribute the most to each impact category during 2005-2010 (bioenergy scenario).

Impact category	Process name	Impact	Impact category	Process name	Impact
Human Heath		DALY	Ecosystems		PDF.m^2.year
	Aluminum, primary, at plant/RER U	1,68E + 05		Aluminum, primary, at plant/RER U	3,76E + 10
	Beef average	1,63E + 05		Barley grains IP, at farm/CH U	2,57E + 10
	Copper, at regional storage/RER U	4,36E + 04		Beef average	3,75E + 11
	Crude oil, at production onshore/RU U	1,64E + 05		Copper, at regional storage/RER U	5,40E + 10
	Egg	3,18E + 04		Corn, at farm/US U	1,26E + 11
	electricity-China	1,89E + 06		Cotton seed, at farm/CN U	2,32E + 10
	electricity-EastAsia	5,16E + 04		Crude oil, at production onshore/RU U	1,68E + 11
	electricity-MENA	5,24E + 04		electricity-China	2,26E + 10
	electricity-NAmerica	1,05E + 05		Folding boxboard, FBB, at plant/RER U	2,51E + 10
	electricity-RestofWorld	5,87E + 04		Ham	1,73E + 11
	electricity-SEAsia	4,91E + 04		Kraft paper, unbleached, at plant/RER U	4,93E + 10
	electricity-SouthAsia	1,17E + 05		Logs, mixed, at forest/RER U	3,40E + 10
	Folding boxboard, FBB, at plant/RER U	3,20E + 04		Nickel, 99.5%, at plant/GLO U	2,68E + 10
	Ham	9,78E + 04		Plywood, indoor use, at plant/RER U	1,35E + 11
	Hard coal, at mine/CN U	4,77E + 05		Plywood, outdoor use, at plant/RER U	1,35E + 11
	Iron ore, 65% Fe, at beneficiation/GLO U	5,57E + 04		Potatoes IP, at farm/CH U	1,07E + 11
	Kraft paper, unbleached, at plant/RER U	3,11E + 04		Potatoes IP, at farm/CH U	3,89E + 10
	Nickel, 99.5%, at plant/GLO U	9,04E + 04		Raisin, viticulture EU	5,02E + 10
	Rice, at farm/US U	5,47E + 04		Rape oil, at oil mill/RER U	3,49E + 10
	Tap water, at user/RER U	3,79E + 04		Rape oil, at oil mill/RER U	2,83E + 10
	Wheat grains IP, at farm/CH U	4,32E + 04		Rape seed IP, at farm/CH U	7,52E + 10
	Wool, sheep, at farm/US U	3,16E + 04		Rape seed IP, at farm/CH U	4,80E + 10
				Rice, at farm/US U	3,51E + 11
		kg CO_2 eq.		Rice, at farm/US U	2,39E + 10
Global Warming	electricity-China	1,68E + 12		Sugar cane, at farm/BR U	4,10E + 10
	Hard coal, at mine/CN U	3,43E + 11		Sugar cane, at farm/BR U	3,70E + 10
	Aluminum, primary, at plant/RER U	3,29E + 11		Sunflower IP, at farm/CH U	2,40E + 10
	electricity-NAmerica	2,52E + 11		Wheat grains IP, at farm/CH U	2,06E + 11
	electricity-RestofWorld	1,87E + 11		Wine	2,00E + 10
	electricity-SEAsia	1,62E + 11		Wool, sheep, at farm/US U	5,85E + 10
	electricity-MENA	1,40E + 11		Zinc, primary, at regional storage/RER U	5,98E + 10
	electricity-SouthAsia	1,25E + 11			
	Beef average	1,14E + 11	Natural Resources		Primary MJ
	electricity-EastAsia	9,44E + 10		Crude oil, at production onshore/RME U	5,95E + 12
	Ham	5,58E + 10		Crude oil, at production onshore/RU U	8,20E + 12
	Crude oil, at production onshore/RU U	5,05E + 10		Hard coal, at mine/CN U	1,44E + 13
	electricity-LatinAmer	4,85E + 10			
	Rice, at farm/US U	4,73E + 10			
	electricity-SSA	4,62E + 10			
	Wheat grains IP, at farm/CH U	3,96E + 10			
	Corn, at farm/US U	3,50E + 10			
	Corrugated board, recycling fiber, double wall, at plant/RER U	3,40E + 10			

that need to be investigated. In this study, instead of modeling 352 processes belonging to the most highly affected economic sectors, identification of processes with the greatest modeled potential environmental impact was reduced to 54 processes. The acquisition of data necessary to improve process modeling has not been made because it was not the purpose of this study. The identification of processes with the greatest modeled potential environmental impact has been made only to illustrate how some results can be used to optimize the final results of the method presented in this paper.

3. A combined modeling approach allows GTAP users to compute detailed potential environmental impacts attributed to economic activities. Some authors have previously included environmental parameters in GTAP but their work focused only on a few pollutants and only emissions to the environment have been modeled rather than potential impacts of emissions on the environment [52–54]. Moreover, these authors used economic sector emissions factor instead of computing emissions from mass of commodity produced or transformed as it has been done here with life cycle assessment methodology. It is expected that GTAP-LCA results are closer to the reality because environmental impacts of each economic sector are modeled according to the life cycle of the processes included in each economic sector. Therefore the variation of contribution of each process in each economic sector in all regions is taken into account which is not necessarily the case when the same economic sector emissions factors are used for all regions.

Many tools have been used in this study: policy scenarios, macroeconomic data, the GTAP model, databases that describe the amount of produced goods (UNDATA, FAO, ForesSTAT, AQUASTAT and IEA), an industrial process database (ecoinvent), and an impact assessment model (Impact2002+). Therefore, it is expected that some uncertainty has been generated by each of these tools. Moreover, mapping of databases with GTAP is an additional source of uncertainty because some processes/commodities were not available in each database and have thus not been included in the study or required other processes to be used as proxy.

Additionally, the ecoinvent database has been primarily developed for modeling European processes. Most of the processes modeled in this study have not been adapted to each region and may not properly model regional realities. However, since ecoinvent is a well recognized and widely used LCA database it was selected for this study. The same limitation is encountered with impact assessment method IMPACT2002+. However, in that case the strength of the results was tested with another impact assessment method (Recipe) and it was found that results obtained with Recipe were concordant with those computed with IMPACT200+.

Another limitation in this study is the lack of accuracy of land use modeling. In its current version, GTAP considers only land occu-

pation for agriculture and livestock, excluding other activities like forestry. Moreover, land surface is fixed and does not increase during simulation to face rising demand of food products. Nonetheless, it is known that significant GHG emissions could occur if natural ecosystems are converted into agricultural land, especially in the case of biofuel production [13,14]. However, the results of this analysis estimate that the EU bioenergy scenario is less effective environmentally than is the business as usual scenario, and therefore taking into account indirect land use changes would be unlikely to change the main conclusions of the study. Incorporation of this aspect would be anticipated only to improve the quality of results, especially GHG emissions.

5. Conclusion

The GTAP model and LCA method have been used together to describe the potential environmental impacts of two European Union energy policies. It was estimated that, at a global scale, the EU bioenergy scenario is environmentally less effective than the EU business as usual scenario. This unexpected result is due to the fact that the EU bioenergy scenario is estimated to have greater enhancing effect on the global economy (especially in China) than would the EU business as usual scenario. In this vein, the EU bioenergy scenario is estimated to have the potential to cause more indirect environmental impacts than would the EU business as usual scenario. In applying the GTAP model, the evolution of the economy is a significantly higher factor than the energy policies themselves in its simulations. Thus, further investigation could be undertaken in identifying how environmental policies could take key drivers of economy into consideration so as to optimize policies environmental outcomes.

The consequential approach presented in this paper benefits both to GTAP model and LCA method. Using this approach allows GTAP model to assess emissions and extractions according to life cycle of products produced by each economic sector instead of using economic sector emissions factor. Moreover chains effects involved in the impact assessment method allow to compute potential impacts to the environment rather than only list the emissions of substances. Thus, the method provides a more accurate description of environmental impacts than using economic sector emission factors. Regarding LCA method, this new consequential approach allows studying significant changes affecting large systems with a global modeling of economy in a time dependent environment (economic growth is taken into account). Results can easily be used to identify which economic sector is responsible of most of the environmental impacts and which regions are mostly affected. Thus results can be improved by collecting certain specific regional and sectoral data.

That said, additional work should be undertaken to quantify and if possible manage all sources of uncertainty. Also, the time horizon of this study should be extended in order to make this approach more prospective. Specifically, economic evolution and technological changes anticipated through 2025 should be considered, including their related uncertainty.

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